Laboratory Evaluation of Dynamic Routing of Air Traffic in an En Route Arrival Metering Environment

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Arrival air traffic operations in the presence of convective weather are subject to uncertainty in aircraft routing and subsequently in flight trajectory predictability. Current management of arrival operations in weather-impacted airspace results in significant flight delay and suspension of arrival metering operations. The Dynamic Routing for Arrivals in Weather (DRAW) concept provides flight route amendment advisories to Traffic Management Coordinators to mitigate the impacts of convective weather on arrival operations. DRAW provides both weather conflict and schedule information for proposed route amendments, allowing air traffic managers to simultaneously evaluate weather avoidance routing and potential schedule and delay impacts. Subject matter experts consisting of retired Traffic Management Coordinators and retired Sector Controllers with arrival metering experience participated in a simulation study of Fort Worth Air Route Traffic Control Center arrival operations. Data were collected for Traffic Management Coordinator and Sector Controller participants over three weeks of simulation activities in October, 2017. Traffic Management Coordinators reported acceptable workload levels, a positive impact on their ability to manage arrival traffic while using DRAW, and initiated weather mitigation reroutes earlier while using DRAW. Sector Controllers also reported acceptable workload levels while using DRAW.

I.   Introduction

Recent advances in air traffic operations and decision support allow for more efficient air traffic operations in the U.S. than previously observed [1,2]. Increased flight path predictability resulting from use of Area Navigation and Required Navigation Performance procedures enables more strategic air traffic management and control. However, to date, the procedures and technologies developed to help controllers and flight crews fully utilize the precision navigational capabilities of modern aircraft are generally not used when convective weather impacts planned flight routes. Arrival flows are nominally planned along known published routes, but deviations from planned routes are often required when convective weather is present. These deviations take two forms: strategic, flow-based solutions coordinated between impacted air traffic facilities and sometimes through the Air Traffic Control System Command Center (ATCSCC), and tactical deviations initiated by either the flight crew or (less often) air traffic controllers to avoid weather in the near future (i.e., <15 minutes to weather conflict). Herein, a weather conflict refers to the predicted path of a flight penetrating convective weather that the flight crew would typically choose to avoid.

Coordinated strategic solutions can be viewed as a temporary redefinition of the nominal routes for a given air traffic flow. Strategies for rerouting aircraft flows around common weather patterns are included in the ATCSCC National Severe Weather Playbook. Such one-size-fits-all solutions are usually effective in avoiding weather conflicts, but often introduce significantly longer flight paths and higher delays. Tactical deviations are sometimes still necessary due to the inherent uncertainties in the weather forecasts used to select routing strategies from the Severe Weather Playbook. Due to this uncertainty, strategic solutions to weather avoidance are often applied conservatively. This can result in larger deviations than necessary to avoid the weather, or deviations with a longer duration than necessary.

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Tactical weather avoidance trades the pitfalls of overly conservative strategic solutions for the risk of acute impacts such as excessive controller and/or flight crew workload, holding patterns or unplanned airspace closures. Whereas tactical weather deviations are sometimes necessary due to weather forecast uncertainty, they reduce the predictability of flight trajectories and the ability to coordinate the movements of multiple flights. Frequent tactical weather avoidance maneuvers prevent the effective use of any technology that relies on flight path predictability. For this reason, arrival metering operations are usually not employed when convective weather impacts Standard Terminal Arrival Routes (STARs) in current operations.

Weather forecast uncertainty will continue to impact air traffic operations for the foreseeable future. Thus, if the operational advancements currently being deployed within the U.S. National Airspace System (NAS) are to be available in the presence of convective weather, solutions are required that enable more responsive weather avoidance routing while maintaining the required flight path predictability.

The remainder of this document is organized to first present the reader with an understanding of the prior research, the need for the integration of dynamic weather routing and time-based flow management capabilities and an overview of the capability developed to fill this need: Dynamic Routes for Arrivals in Weather (DRAW) (Section II). With an understanding of the potential utility of the integrated weather avoidance capability toward more strategic weather impact mitigation, the reader is next presented with the experimental methodology employed to evaluate the proposed decision support tool (Section III). Results of the experiment are provided in Section IV along with discussion of their relevance to and impact on future research and development activities. Lastly, concluding remarks and a brief discussion of future research are presented in Section V.

II.   Background

This section provides a brief overview of the research that preceded the development of DRAW as well as a brief overview of the DRAW concept for integrated dynamic weather-avoidance routing and time-based metering. Two areas of prior research are presented, (A) Dynamic weather-avoidance routing and (B) Time-Based Flow Management (TBFM), followed by (C) a DRAW concept overview.

A. Dynamic Weather Avoidance Routing

Massachusetts Institute of Technology Lincoln Laboratory (MITLL) research led to the development of the Convective Weather Avoidance Model (CWAM) [3]. Using Corridor Integrated Weather System forecasts and empirical observations of pilot weather avoidance behavior, CWAM provides a probabilistic model of convective weather regions flight crews are likely to avoid, called Weather Avoidance Fields (WAFs). CWAM WAFs are used by the MITLL Route Availability and Planning Tool and the Arrival Route Status and Impact concept to predict route availability in the presence of weather for static, published departure and arrival routing, respectively [4,5]. Prete, et. al., proposed a dynamic programming approach to finding available routing that used simulated Markov chain propagation of convective weather. This concept was tested in simulation for controller and pilot acceptability; however, the performance of the weather propagation algorithm and subsequent avoidance efficacy was not evaluated [6].

NASA developed the Dynamic Weather Routes (DWR) tool to provide Airline Operations Centers (AOCs) and flight dispatchers with more efficient departure and en route routing. DWR uses forecast CWAM WAFs and predicted flight trajectories to generate more efficient, weather-conflict-free routes for departures and overflights. DWR does not address arrival flight weather avoidance, nor does it consider air traffic control/air traffic management (ATC/ATM) implications of proposed route changes [7-9].

B. Time-Based Flow Management (TBFM)

The Traffic Management Advisor (TMA) was developed by NASA in collaboration with the Federal Aviation Administration (FAA) and currently forms the basis for time-based metering of arrival air traffic into Terminal Radar Approach Control (TRACON) facilities [10]. Air Route Traffic Control Center (ARTCC, or Center) controllers employ TMA-provided delay values for each flight to meet a schedule of arrivals into terminal airspace that complies with necessary arrival constraints (e.g., airport arrival rates). Recent efforts have built on the TMA foundation to improve the efficiency and predictability of arrival operations.

Whereas TMA provides effective arrival metering into TRACON airspace, it does not provide any information to TRACON controllers for implementation of the schedule. TMA was developed prior to the more recent roll-out of arrival procedures requiring Performance Based Navigation (PBN) capabilities. Thus, TRACON controllers need to

make tactical adjustments (e.g., heading vectors, step-down descents and speed assignments) to flight paths between the metering fix and the approach to separate and space arrival aircraft. PBN arrival procedures are intended to provide significant improvements in predictability and efficiency maintaining a prescribed aircraft route and efficient descent profile from the cruise phase of flight to final approach; speed adjustments are the preferred method for spacing and separating arrival flights in PBN operations.

The Terminal Sequencing and Spacing (TSAS) concept enhances the TMA scheduler to account for the limited control authority of speed adjustments along PBN procedures and additionally provides tools for controllers to effectively space aircraft along PBN routes using predominantly speed adjustments. TSAS was evaluated in high-fidelity laboratory simulations, refined through limited operational trials, was formally transferred to the FAA and is to be included in the FAA TBFM deployment over the next few years [1,2].

C. DRAW Concept Overview

The DRAW system is based on the foundation of the DWR concept and shares a number of the DWR components. Both DRAW and DWR provide trajectory-based routing solutions to avoid CWAM WAFs. DWR was developed to provide weather-avoidance routing to AOC personnel, whereas DRAW is designed to integrate weather-avoidance routing and TBFM for arrival flights, and thus employed by air traffic personnel in the ARTCC Traffic Management Unit (TMU). The integration of weather avoidance routing and arrival metering is seen as a necessary step to enabling TBFM in weather-impacted airspace. DRAW meets this need by providing weather avoidance routing that is more responsive than playbook operations and results in more predictable flight trajectories than tactical weather avoidance. This subsection provides a brief overview of the core DRAW elements. Ref. [11] provides a more detailed description of the DRAW concept.

DRAW is an advisory-based system that proposes route amendments to Traffic Management Coordinators (TMCs) in the ARTCC TMU. Proposed route amendments take two forms: more efficient routing to an alternate arrival metering fix or arrival transition, and weather-avoidance reroutes that modify the flight path without changing the flight plan arrival procedure or transition. Reroutes to alternate metering fixes occur when the cleared route of flight has a longer flight path than the proposed alternate arrival path (e.g., due to a no-longer-necessary Playbook route); alternate arrival reroutes are not proposed for weather avoidance, but simply to reduce flight time. Weather-avoidance reroute advisories, on the other hand, occur when the cleared route is predicted to penetrate CWAM WAFs; these reroutes may or may not change arrival procedure.

Proposed route amendments are updated every 12 seconds with each ARTCC flight track update cycle and provided to the TMC in an advisory list on a TMU map display. The advisory list provides basic information for each advisory, including: Flight callsign, proposed arrival procedure and transition, flight time savings/delay resulting from the proposed reroute, and the type of advisory (e.g., more efficient routing, weather-avoidance routing). TMCs select individual advisories or a group of advisories for evaluation and employ a trial planning interface to modify the proposed route amendment as necessary to satisfy operational constraints (e.g., to select a different STAR, transition for a given STAR, or initial capture fix). As the TMC evaluates and/or modifies the proposed route amendment, weather avoidance status and metering schedule impact are provided to the TMC to aid evaluation and/or modification.

The continuous, simultaneous feedback on weather avoidance status and schedule impact for the proposed route amendment is the key innovation of the DRAW concept. Figure 1 shows graphical feedback presented to a TMC while evaluating a DRAW reroute advisory; the figure depicts the current flight plan route (green line) and a reroute (dashed yellow line) that successfully avoids forecast CWAM WAFs. Figure 2 provides sample schedule feedback for a trial plan evaluation as would be seen by the TMC on the schedule timeline display; in this example, two timelines are shown, one for each arrival meter fix. Estimated times of arrival (ETA) at the arrival meter fix are on the left of each timeline, whereas scheduled times of arrival (STA) are on the right. Figure 2 depicts the STA for the flight of interest in magenta text (current flight plan) and block magenta lettering (proposed reroute). In this example, the suggestion is to move the flight of interest from one arrival meter fix depicted on the right timeline to another depicted on the left timeline. With both weather-avoidance and schedule impact feedback, the TMC is able to quickly evaluate advisory acceptability and to arrive at a rerouting decision.
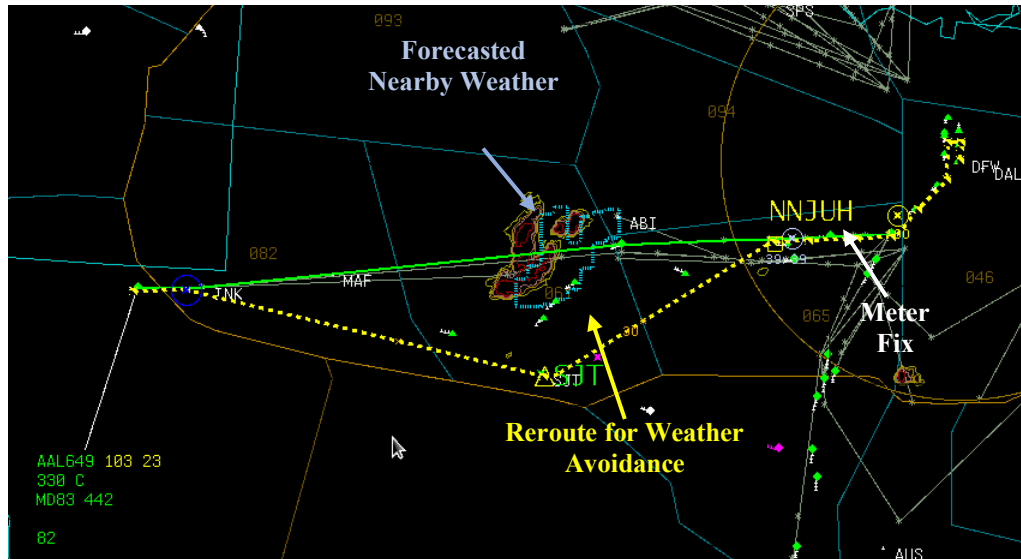
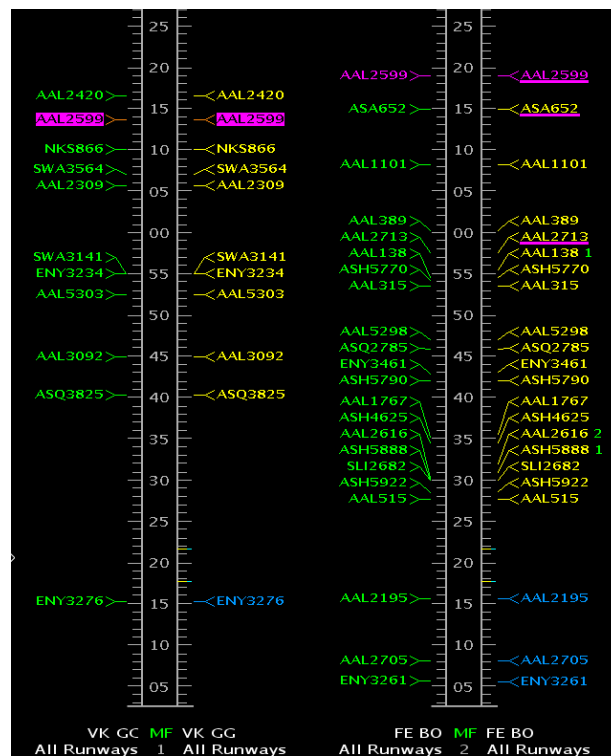**Fig. 1 Trial Plan Avoiding Weather and Rejoining Arrival**

Fig. 2 Schedule Impact Feedback for Alternate Meter Fix Reroute

The DRAW concept was previously evaluated in a series of simulations and storyboarding activities in early 2017. Feedback from TMCs in this earlier activity were useful in identifying beneficial use cases, refining the DRAW concept of operations, improving simulation training procedures, and identifying additional capabilities to enhance DRAW usability.

III. Methodology

This section presents the study methodology employed to evaluate DRAW operations in the NASA Ames Research Center ATC Laboratory. An overview of the ATC Laboratory configuration for DRAW evaluation is provided, followed by the experimental setup, including details of the study airspace, traffic scenarios, participants, and experimental design.

A. ATC Laboratory Configuration

The Air Traffic Control Laboratory (ATC Lab) can simulate either TRACON and/or ARTCC operations. As configured for DRAW, the ATC Lab consists of seven En Route Automation Modernization (ERAM) stations, seven pseudo-pilot stations, two TMU stations, a Simulation Manager position and a Tactical Weather Avoidance position. Figure 3 depicts the ATC Lab configurations employed in this study. Two configurations were used, as will be discussed in a following section.

ERAM stations are staffed by sector controller participants and are intended as sufficiently accurate representations of ERAM consoles in operational use in the ARTCC. ERAM stations include a traffic display, keyboard, trackball and voice communication hardware.

Each TMU station consists of a keyboard, mouse and two displays: a plan-view graphical user interface map display and a timeline display generated by Center-TRACON Automation System (CTAS). The TMC staffing a TMU station interacts with the DRAW system as previously described.

Multi Aircraft Control System (MACS) pseudo-pilot stations are used to control multiple flights as instructed by the participant controllers via electronic voice communication (emulating VHF voice communication). Pseudo-pilots employ a multiple-flight interface and are assigned to execute all clearances given for flights owned by a single sector controller.

The Tactical Weather Avoidance position provides tactical weather avoidance capability to approximate the behavior of flight crews acting to avoid convective weather within about 80nm of flight position. Any necessary weather avoidance maneuvers are communicated to the pseudo-pilot and are subsequently requested as weather deviations to the sector controller.

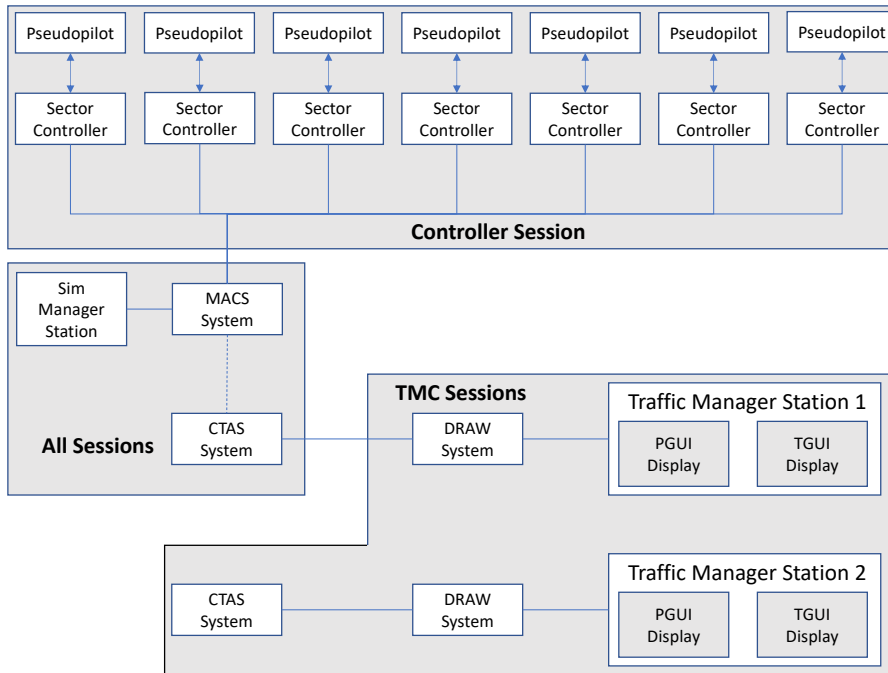The Simulation Manager station is used by research staff to monitor simulation conduct.

Fig. 3 ATC Laboratory DRAW Configurations

B. Experimental Setup

1. Airspace and Traffic Scenarios

Simulations for this study were conducted in the context of Fort Worth (ZFW) ARTCC. Arrival traffic for Dallas-Fort Worth International Airport (DFW) and Dallas Love Field, DFW departures, and ZFW overflight traffic were included in all scenarios. ZFW sectors along the Glen Rose (Southwest) and Bowie (Northwest) arrival flows were staffed with participant controllers (described below).

2. Independent TMC-Sector Control Approach

The study was conducted in two sessions. In TMC sessions, where only TMCs participated, the actions of TMCs to reroute flights around weather were recorded, which were later used to create input scenarios for the Controller session. TMC reroutes were implemented prior to flights entering sector controller airspace. The Controller session included only sector controller participants. The purpose of this approach was to limit scenario length and increase the number of runs in the one-week study period.

3. Participants

Two retired ZFW TMCs participated in each of the two, three-day TMC sessions, or 4 TMCs in total. Experience as ARTCC TMCs ranged from three to eight years (mean = 5.3 years). They retired within the last seven years (mean = 3 years). In addition, seven retired sector controllers participated in the Controller session. One of them was a retired Area Supervisor of ZFW. Three others retired from Oakland ARTCC (ZOA), and three others retired from Los Angeles ARTCC (ZLA). Controller ARTCC experience ranged from 16 to 28 years (mean = 24 years). They retired from ARTCC within the last eight years (mean = 5 years). Eight pilot participants were recruited from the local general-aviation community to perform the pseudo-pilot duty in the simulation.

4. Experimental Design

Two TMC sessions were conducted, each including 16 runs with two TMCs, or in total 32 runs with four TMCs. During the TMC sessions, the ATC Lab was configured with two TMC stations such that two TMCs could operate concurrently (see Figure 3). The TMC runs included three independent variables: Tool Condition (DRAW vs No DRAW), Traffic Scenario (1 vs 2), and TMC Participant (A, B, C, and D). A total of 16 TMC runs were conducted (2x2x4 design) in the two TMC sessions with the run order being counterbalanced for the scenario condition both within and between subjects; TMC-Controller runs were those runs conducted in the TMC sessions that were utilized to generate input scenarios for the Controller session. Only the eight TMC runs conducted during Session 1 were used in the following Controller session; this assignment was made prior to TMC Session 1.

An additional eight runs were conducted in the TMC sessions with four additional scenarios (3, 4, 5, and 6) and two TMCs (A, B, C, and D) (4x2); these runs were all conducted with the DRAW condition and only employed for TMC data analysis to obtain TMC feedback on DRAW use across a broader range of conditions.

The Controller session employed a 2x2x2x2 design with the following main effects: Tool Condition (DRAW vs No-DRAW), Scenario (1 vs 2), TMC (A vs B), and Controller Seating (1 vs 2). Controller session run order was counterbalanced for Tool Condition, Scenario and TMC conditions for both within and between Controller Seating condition.

Data were collected for both TMC and Controller sessions to evaluate the performance of the DRAW system, to obtain TMC feedback on the acceptability of DRAW advisories, and to assess the impact of DRAW on metered arrival air traffic operations.

IV. Results

The following analyses are summarized: A) reroute timing, B) weather avoidance, and C) human factors.

A. Reroute Timing

TMCs were provided with a trial planning functionality to assist with reroute decisions in both the DRAW and No-DRAW test conditions. However, whereas the DRAW trial planning functionality included means to modify and amend a route with an indication of predicted CWAM WAF penetrations (as well as schedule impact information), the No-DRAW trial planning functionality only included the means to modify and amend the route. It was hypothesized that the additional weather conflict and schedule impact information would allow TMCs to reroute aircraft at an earlier time than without DRAW. Reroute times were computed as the estimated time to fly from a flight's position at the moment a route is amended to the arrival metering fix. Evaluation times were computed in a similar fashion. Data showed that TMCs evaluated reroutes earlier with DRAW (80 minutes estimated time to meter

fix) than without (64 minutes estimated time to meter fix). An independent-samples *t*-test result indicated that the difference is statistically significant (t(30) = -7.07, p < 0.001). Results also showed that TMCs rerouted aircraft earlier with DRAW (81 minutes estimated time to meter fix) than without (66 minutes estimated time to meter fix), which was also statistically significant (t(30) = -7.88, p<.0001). Thus, reroute timing data indicate TMCs both considered potential reroutes earlier and acted earlier on acceptable reroutes when using DRAW than when DRAW was not available. Mean reroute times were earlier than mean evaluation times because TMCs evaluated nearly all DRAW advisories but tended to reject advisories first presented near the ZFW boundary.

B. Weather Avoidance

TMC reroute actions were recorded for both DRAW and No-DRAW test conditions. For each TMC-Controller run, flightpaths were simulated that included all TMC reroute actions, but no controller actions. The resultant flight trajectories were analyzed to detect weather conflicts where the simulated flight path penetrated CWAM WAFs in ZFW ARTCC airspace. Because TMCs typically choose not to reroute flights with minor deviations necessary to avoid weather, only those weather conflicts that required lateral deviations in excess of 5nm were recorded. These weather conflicts represent those that remain after TMC reroute actions and that must be resolved tactically by the flight crew and/or sector controller(s). A comparison of DRAW and No-DRAW runs showed that DRAW had fewer weather conflicts remaining for controller/pilots to resolve (5.6 per run) than No-DRAW (10.8) (t(14) = 2.29, p<.0383). This finding demonstrates that, whereas TMCs rerouted aircraft earlier with DRAW, earlier action did not tend to increase the number of weather conflicts remaining as one might suspect. Figure 4 depicts the number of weather conflicts remaining for pilots and controllers to resolve for each of the 16 TMC-Controller runs, by Controller Seat (S1 vs. S2) and by TMC (A, B, C, and D); DRAW had the same or fewer remaining weather conflicts in each condition.
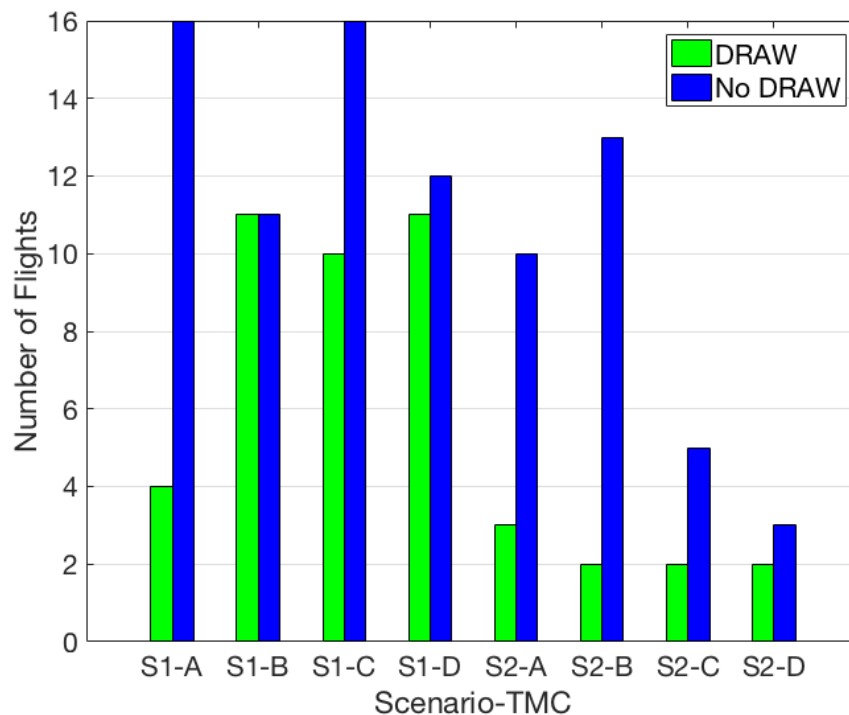

Fig. 4 DRAW Effect on Weather Conflicts Remaining for Pilots and Controllers to Resolve

C. Human Factors

Post-run questionnaires were administered after each run of both the TMC and Controller sessions. Five questions were asked to determine TMC acceptability of DRAW operations; a 7-point Likert scale was used for each question (from 1-Strongly Disagree, to 7-Strongly Agree). Table 1 provides an overview of the questions and the summary statistics. The data show similar results for TMC-Controller and TMC-Only runs. The means of the Q1, Q2, and Q3

responses were relatively high in both TMC-Controller and TMC-Only runs (> 6 in 7-point scale), whereas those of the Q4 and Q5 responses were relatively low (< 5.5) in both types of runs. This implies that TMCs thought DRAW operations were acceptable in terms of TMC workload (Q1), timing of DRAW advisory presentation (Q2), and DRAW generally being helpful for arrival management in weather (Q3). On the other hand, TMCs did not feel strongly that DRAW would increase the probability of sustaining arrival metering in weather (Q4) or that DRAW would delay the need for other traffic management initiatives (Q5).

Table 1 TMC Acceptability of DRAW Operations

Question	TMC-Controller Runs Mean (Stdv, N)	TMC-Only Runs Mean (Stdv, N)
Q1: TMC-workload due to the DRAW tasks was acceptable.	6.4 (0.74, 8)	6.3 (0.58, 16)
Q2: DRAW advisories were provided early enough for me to perform efficient rerouting.	6.5 (0.53, 8)	6.3 (0.58, 16)
Q3: DRAW improved my ability to manage arrival traffic in weather.	6.4 (0.74, 8)	6.2 (0.16, 16)
Q4: DRAW would increase probability of sustaining arrival metering in weather.	4.9 (0.99, 8)	5.0 (0.63, 16)
Q5: DRAW would delay need for other TMIs (e.g., MIT, Playbook).	4.9 (1.1, 8)	5.2 (0.75, 16)

Controller workload was assessed during each Controller session run using the Workload Assessment Keypad (WAK) [12] and following each Controller session run using the NASA Task Load Index (TLX) ratings [13]. No DRAW effect was observed in sector controllers' real-time workload ratings measured via WAK. NASA TLX ratings consist of six subscale ratings, each on a 0-to-10 scale. Table 2 provides the summary NASA TLX data.

Table 1 NASA TLX Controller Mean Workload Ratings

Rating	DRAW runs (Stdv)	No-DRAW runs (Stdv)
Mental Demand	4.9 (2.7)	5.0 (2.4)
Physical Demand	4.7 (2.7)	5.0 (2.5)
Temporal Demand	4.4 (2.6)	4.5 (2.5)
Performance (reversed)	3.9 (2.7)	3.2 (2.5)
Effort	4.8 (2.8)	4.7 (2.6)
Frustration	3.1 (2.8)	2.9 (2.6)

Linear Mixed Model (LMM) regression analysis of controller TLX ratings detected two statistically significant DRAW-related effects. Use of DRAW was observed to have a significant effect on the NASA TLX Performance subscale rating, with controllers rating their performance poorer when using DRAW; it is unclear why controllers reported their performance lower with DRAW than without (p=0.048). On the other hand, DRAW effect was observed to lower Mental Demand workload rating for the Sector 47 controller (p=0.029). Lower Mental Demand workload for the Sector 47 controller could imply more effective rerouting or demand balancing between arrivals, as this Sector experienced a high number of reroutes during Scenario 2.

Significant Sector and Scenario effects in various NASA-TLX subscale ratings were also observed which were consistent with traffic levels in each sector dictated by the corresponding scenarios.

V.   Conclusion

As previously discussed, procedures and technologies intended to fully utilize the precise navigational capabilities of modern aircraft are subject to weather-induced uncertainties that preclude their use in airspace impacted by convective weather activity. DRAW is designed to mitigate the impact of these uncertainties by providing TMCs with the ability to develop flight reroutes that simultaneously avoid convective weather and satisfy arrival scheduling constraints. Separate TMC and Controller simulation sessions were used to evaluate DRAW and its impact on arrival

metering operations in the ZFW airspace. Results indicate that TMCs acted earlier to mitigate the impact of convective weather on arrival operations by evaluating and rerouting flights earlier with DRAW than without. Results also showed that this earlier rerouting did not tend to increase the number of weather conflicts remaining as one might suspect. Lastly, TMCs reported their workload and DRAW advisory timing acceptable while finding DRAW generally helpful for arrival management in weather. However, TMCs did not report that DRAW would sustain arrival metering operations or delay the need for other traffic management initiatives. Sustaining arrival metering operations and delaying the need for traffic management initiatives are viewed as key benefits of DRAW. However, challenges remain with assessing these benefits due to difficulties in simulating realistic arrival metering operations.

Additional studies are planned to further refine the DRAW concept and to identify practical use cases for DRAW in current and future arrival operations. Both human-in-the-loop and closed-loop simulation analyses are planned to evaluate DRAW in different airspace and with varied traffic and convective weather characteristics. Finally, NASA is working closely with the FAA to develop the concept for DRAW use in the future TBFM environment that includes extended metering and coupled scheduling for arrivals across multiple ARTCCs.

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